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AUTHORITY

28 Feb 2007, per document marking

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Novel Image Quality Control Systems(Add-On). Innovative Computational Methods for Inverse Problems in Optical and SAR Imaging

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6. AUTHORS
Robert J. Plemmons

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13. ABSTRACT (Maximum 200 words)
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14. SUBJECT TERMS
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Report Title

Novel Image Quality Control Systems(Add-Ons).
Innovative Computational Methods for Inverse Problems in Optical and SAR Imaging.

ABSTRACT

The objectives of this project were to conduct rigorous mathematical and computational research on inverse problems in optical imaging of direct interest to the Army and also the intelligence agencies. Research problems included research on integrated optical systems design, array imaging, and related technologies. Our technique of combining optical/electronic hardware with digital processing is associated with our work on Pupil-Phase Engineering (PPE), for which we have a patent pending. The ARO project was primarily funded over the last three years by supplements from the Biometrics Division at the NSA, the Intelligence Technology Innovation Center at the CIA, and the Disruptive Technology Office. Technology transfer included the transition of our work to the ARL, to the Army Night Vision Lab, and to biometrics groups at the NSA and CIA. Industrial technology transfer took place with Iridian Technologies Co., CDM-Optics Inc., and Sarnoff Corp.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

W. Cochran, R. Plemmons and T. Torgersen. Exploiting Toeplitz Structure in Image Restoration, Contemporary Mathematics, Vol. 280, pp. 177-198, 2001.

S. Prasad. Statistical Information Based Performance Criteria for Lucy Richardson Image Deblurring, J. Opt. Soc. Amer. A, vol. 19, pp. 1286-1296, 2002.

P. Pauca, A. Rodriguez, X. Sun, and K. Trivedi. A Methodology Towards Automatic Implementation of N-body Algorithms. Applied Numerical Mathematics, vol. 40, pp. 3-21, 2002.

M. Chu and R. Plemmons. Real-Valued Low Rank Circulant Approximation. Soc. for Industrial and Appl. Math J. on Matrix Analysis and Applic., vol. 24, pp. 645-659, 2002.

T. Torgersen and D. Tyler. Practical Considerations for Restoring Images from Phase-Diverse Speckle Data, Astonomical Soc. Pacific, vol. 114, pp. 671-685, 2002.

M. Chu, R. Funderlic and R. J. Plemmons. Structured Low Rank Approximation, Lin. Alg. and Applications, Vol. 366, pp. 157-172, 2003.

J.Mait, R. Athale, and J. van der Gracht. Evolutionary Paths in Imaging and Recent Trends, Optics Express, vol. 11, pp. 2093-2101, 2003.

S. Prasad, T. Torgersen, V. P. Pauca, R. J. Plemmons, and J. van der Gratch. Restoring Images with Space Variant Blur via Pupil Phase Engineering, Optics in Information Systems, Special Issue on Computer Imaging, vol. 4, no. 2, pp. 4-5, 2003.

J. Yuan, G. Golub, R. Plemmons, and W. Cecilio. Semi-Conjugate Direction Methods for Real Positive Definite Systems, BIT Numerical Mathematics, Vol. 44, pp. 189-207, 2004.

S. Prasad. Fisher Information Based Analysis of a Phase Diversity Speckle Imaging System, J. Opt. Soc. Am. A, vol. 21, pp. 2073-2088, 2004.

M. Catral, Lixing Han, Michael Neumann and Robert Plemmons. On Reduced Rank Nonnegative Matrix Factorization for Summarizing Video Sequences, Linear Algebra and Applications, Vol. 393, pp. 107-126, 2004.

S. Prasad and N. Menicucci. Fisher Information with respect to Cumulants, IEEE Trans. Information Theory, Vol. 50, pp. 638-647, 2004.

S. Prasad. Information optimized phase diversity speckle imaging, Optics Letters, Vol. 29, pp. 563-572, 2004.

S. Prasad, T. Torgersen, P. Pauca, R. Plemmons and J. van der Gracht. High-Resolution Imaging Using Integrated Optical Systems, International Journal on Imaging Systems and Technology, Vol. 14, No. 2, pp. 67-74, 2004. (invited paper)

M. Chu and R. Plemmons. Nonnegative Matrix Factorization and Applications, Bulletin of the International Linear Algebra Society, pp. 2-7, 2005. (invited paper)

S. Shahnaz, M. Berry, P. Pauca, and R. Plemmons. Document Clustering using Nonnegative Matrix Factorization, Information Processing and Management, Vol. 42, pp. 373-386, 2006.

J. Bardsley, S. Jefferies, J. Nagy, and R. Plemmons. A Computational Method for the Restoration of Images with an Unknown, Spatially-Varying Blur, Optics Express, Vol. 14, no. 5, pp. 1767-1782, 2006.

Z. Mu, R. Plemmons, and P. Santago. Iterative Ultrasonic Signal and Image Deconvolution for Estimation of the Complex Medium Response, International Journal of Imaging Systems and Technology, Vol. 15, no. 6, pp. 266-266, 2006.

P. Pauca, J. Piper, and R. Plemmons. Nonnegative matrix factorization for spectral data analysis, Linear Algebra and Applications, Vol. 416, pp. 29-47, 2006.

R. Plemmons. Inverse Problems in Imaging, in Computer Mathematics and Applications: Advances and Developments, Edited by E. Lipitakis, LEA Press, Athens, Greece, pp. 195-204, 2006.

Number of Papers published in peer-reviewed journals: 20.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

No papers published in non-peer-reviewed journals.

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

R. Plemmons, "Inverse Problems in Imaging", SIAM Conference on Computational Science and Engineering, Washington, DC, September 2000.

R. Plemmons, et al., “Structured Matrix Computations in Adaptive Optics”, International Conference on Structured Matrices, Cortona, Italy, October 2000.

R. Plemmons, “Imaging Through Turbulence, SIAM Conference on Applied Linear Algebra, Raleigh, NC, October 2000.

R. Plemmons, et al., “Topics in Optical Image Reconstruction”, DOD Workshop on Ground-Based Imaging, Maui, HI, December 2000.

R. Plemmoms, “Algorithms and Software for High Resolution Imaging”, International Conference on Mathematics and Computers, Patras, Crete, May 2001.

R. Plemmons, et al., “Comparison of Iterative Methods for Inverse Problems in Imaging”, IMACS Conference on Iterative Methods, Heraklion, Crete, May 2001.

R. Plemmons, “Inverse Problems in Optical Imaging”, International Conference on Inverse Problems, Tuscany, Italy, June 2001.

R. Plemmons, “Algorithms for High Resolution Imaging”, Workshop on Space Object Imaging, Albuquerque, NM, July 2002.

R. Plemmons, et al., “Extended Focus Image Reconstruction”, AMS-IMS-SIAM Summer Research Conference, South Hadley, MA, August 2001.

R. Plemmons, “Numerical Linear Algebra in Imaging”, SIAM Conference on Signals, Systems and Control, Boston, MA, August 2001.

R. Plemmons, “Optimization Methods in Imaging”, International Workshop on Optimization, Curitiba, Brazil, August 2001.

R. Plemmons, et al., “Phase Estimation and Applications”, NASA/DOD Workshop on New Directions for Imaging, Huntsville, AL, September 2001.

R. Plemmons, et al., “Restoring Extended Focus Imagery”, Briefing for the National Security Agency on Personnel Identification and Verification Systems, Ft. Meade, MD, October 2001.

R. Plemmons, “3D Restoration of Tomosynthetic Images”, Optical Society of America Topical Meeting, Albuquerque, NM, November 2001.

R. Plemmons, et al., “Phase Estimation in Optical Imaging”, Southeast USA Conference on Applied Mathematics, Raleigh, NC, November 2001.

R. Plemmons, “Phase Array Computations and Applications”, DOD Workshop on Space Situational Awareness, Maui, HI, January 2002.

R. Plemmons, et al., “An Optimal Design Problem in Optics”, Boeing Optimization Workshop, Seattle, WA, February, 2002.

R. Plemmons, “Structured Matrices in Imaging”, International. Conf. on Structured Matrices, Hong Kong, May, 2003

R. Plemmons, “Nonlinear Optimization in Imaging Science”, (3 lectures) MSRC Tech. Workshop, Maui, HI, June, 2002.

R. Plemmons, “New Directions in Integrated Optical Imaging”, SPIE Annual Meeting Seattle, WA, July, 2003.

R. Plemmons, et al., “Inverse Problems in Optical Design”, International Conference on Inverse Problems, Strobl, Austria, August, 2003.

Joseph van der Gracht, et al., "Wavefront Manipulation in Imaging: When Blurry is Better", 2003 Proceedings of the Annual Meeting of the Optical Society of America, p. 124 (summary abstract only published), invited presentation.

S. Prasad, et al., "Engineering the Pupil Phase to Improve the Quality of Digitally Restored Images", 7th US National Congress on Computational Mechanics, Albuquerque, NM, July 28-30, 2003, invited presentation.

S. Prasad, "An Information Theoretic Analysis of Integrated Imaging Systems", Workshop on Inverse Problems at the Institute for Pure and Applied Mathematics, Univ. of California at Los Angeles (UCLA), Los Angeles, CA, October 21, 2003, invited presentation.

R. Plemmons, "Mining Scientific Data", Workshop on Space Situational Awareness, Maui HI, January 2003.

R. Plemmons, et al., "Image Quality Control by Pupil Phase Engineering", 5th International Congress on Industrial and Applied Mathematics (ICIAM), Sydney, Australia, July 2003, invited presentation.

R. Plemmons, et al., "Integrated Optical-Digital Approach for Enhancing Image Restoration", Workshop on Inverse Problems at the Institute for Pure and Applied Mathematics, Univ. of California at Los Angeles (UCLA), Los Angeles, CA, October 2003, invited presentation.

R. Plemmons, "Image Restoration using Integrated Optics Systems", International Conference on Imaging Science, Singapore, Dec. 2003, invited presentation.

R. Plemmons, "Content Based Image Data Retrieval and Classification using Nonnegative Encoding", International Workshop on Imaging Science, Singapore, Dec. 2003, invited presentation.

Harsha Setty, et al., "Pupil Phase Engineering for Improving Iris Recognition Technology", 2003 Duke University Fitzpatrick Center for Photonics and Communications Systems Annual Symposium, invited presentation.

T. Torgersen, et al., "Engineering the Pupil Phase to Improve Image Quality", 5th International Congress for Industrial and Applied Mathematics (ICIAM), July 2003, Sydney, Australia, invited presentation.

R. Plemmons, et al., “Non-imaging Identification and Classification of Space Objects from Spectral Sensor Data”, Fitzpatrick Center Conf. on Physics of Information, Durham, NC, May 2004.

S. Prasad, “Fisher-information Optimized Phase Diversity Speckle Imaging," an invited presentation at the 2004 SIAM Conf. on Imaging Science, Salt Lake City, UT, May 3-5, 2004.

R. Plemmons, “Low-Rank Nonnegative Matrix Factorization for Spectral Imaging,” International Conf. on Imaging Science, Cortona, Italy, September 2004.

T. Torgersen, “Pupil Phase Engineering for Extending the Depth-of Focus”, Southeastern Optical Society of America Conf., Charlotte, NC, October 2004.

R. Plemmons, et al., "Low-Rank Nonnegative Matrix Factorization for Spectral Imaging," International Conf. on Imaging Science, Cortona Italy, September 2004.

T. Torgersen, et al., "Pupil Phase Engineering for Extending the Depth-of Focus", Southeastern Optical Society of America Conf., Charlotte NC, October 2004.

R. Plemmons, et al., "Nonnegative Matrix Factorizations and Applications," Haifa Matrix Theory Conference, Haifa, Israel, January 2005.

R. Plemmons, et al., "Computational Imaging Systems for Iris Recognition,"Workshop on Iris Recognition Systems, McLean VA, February 2005.

P. Pauca, et al., "Optical-Digital Approach for Enhanced Biometric Imaging" SIAM Conference in Computational Science & Engineering, Orlando FL, February 2005.

J. van der Gracht, et al., "Iris recognition with enhanced depth-of-field image acquisition," invited presentation, Biometrics Meeting, Mitre Corp., McClean, Virginia, February, 2005.

R. Plemmons et al., "High-Resolution Compound Imaging Systems," ARDA Workshop on Advanced Imaging, Oak Ridge National Laboratory, TN, March 2005.

D. Fan, et al., "Phase masks for iris recognition systems", Optical Society of America Conference on Computational Optical Sensing and Imaging, Charlotte NC, June 2005. (D. Fan was a graduate student who worked on the ARO grant iris recognition project).

R. Plemmons et al., "Array Imaging for Superresolution," International Conference on Superresolution Imaging, Hong Kong, China, August 2005.

S. Prasad et al., "Optical Preconditioning and Digital Image Restoration," Annual SPIE Conference on Unconventional Imaging, San Diego, CA, August, 2005.

R. Plemmons et al., "The PERIODIC System for High Resolution and Low Profile Imaging," Optical Society of America, Atlanta, GA, October 2005.

R. Plemmons, "Algorithms and Theory for Nonnegative Matrix Factorizations in Data Mining," International Conference on Computational Statistics, Limassol, Cyprus, October 2005.

R. Plemmons, "Some Computational Issues in Spectral Imaging," invited talk presented at the SIAM Imaging Science Conference, Minneapolis, MN, May 15-17, 2006.

S. Prasad, "A Taxonomy of Cramer-Rao Bounds and Their Applications to Imaging," invited talk presented at the SIAM Imaging Science Conference, Minneapolis, MN, 2006.

R. Plemmons et al., "Low-Rank Nonnegative Factorizations for Spectral Imaging Applications", Invited Talk at the Stanford Workshop on Algorithms for Modern Massive Data Sets, Palo Alto, CA, June 2006.

R. Plemmons, et al., "Nonnegative Matrix and Nonnegative Tensor Factorizations, with Applications," Invited Lecture at the International Conference on Nonnegative Matrices and Applications, Maynooth, Ireland, July 2006.

R. Plemmons, et al., "Nonnegative Tensor Factorizations," Invited Lecture at the International Linear Algebra Society 13th Annual Conference, Amsterdam, The Netherlands, July 2006.

R. Plemmons, et al., “Spectral Un-mixing for Object Identification”. Invited Lecture, SIAM Southeast Asia Conference, Sapporo, Japan, July 2006.

R. Plemmons, et al., “Tensor Factorization Methods for Image Anlaysis”. Symposium on Advanced Imaging in Medicine, Riken Brain Science Institute, Tokyo, Japan, July 2006

R. Plemmons, et al., “Tensor Methods for Data Compression and Anlaysis”. National Institute for Statistical Sciences, Research Triangle Park, NC, February, 2007.

Number of Presentations: 55.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

No non peer-reviewed conference proceeding publications (other than abstracts).

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

P. Mu and R. Plemmons. Regularization Methods for Image Reconstruction Based on Autocorrelation Functions, Proc. SPIE Symposium on Optical Science and Technology, San Diego, CA, vol. 4116, pp. 111-120, 2000.

J. van der Gratch, J. Nagy, P. Pauca and R. Plemmons. Iterative Restoration of Wavefront Coded Imagery for Focus Invariance. OSA Trends in Optics and Photonics (TOPS), Integrated Computational Imaging Systems, OSA Technical Digest, Washington, D.C., 2001.

P. Hemler, T. Persons and R. Plemmons. 3D Iterative Restoration of Tomosynthetic Images. OSA Trends in Optics and Photonics (TOPS), Integrated Computational Imaging Systems, OSA Technical Digest, Washington, D.C., 2001.

J. van der Gratch, G. Euliss and P. Pauca. Experimental Investigation of Aliasing in the Assessment of Sampled Images. Proc. SPIE AeroSense Conference, Visual Information Processing XI, vol. 4736, pp. 99-106, 2002.

S. Prasad, R. Plemmons, P. Pauca and T. Torgersen. Integrated Optics Systems for Image Quality Control, Proc. AMOS Tech. Conf., Maui, HI, September, 2002.

Z. Mu, R. Plemmons, and P. Santago. Estimation of Complex Ultrasonic Medium Responses by Deconvolution, Proc. IEEE Inter. Symp. on Biomedical Imaging, pp. 1047-1050, 2002.

S. Prasad, T. Torgersen, P. Pauca, R. Plemmons, and J. van der Gracht. Engineering the pupil phase to improve image quality, in Proceedings of the SPIE Vol. 5108 Visual Information Processing XII, edited by Z. Rahman, R. Schowengerdt, and S. Reichenbach (SPIE, Wellingham, WA, pp. 1-12, 2003.

P. Pauca, S. Prasad, R. Plemmons, T. Torgersen J. van der Gratch, and C. Vogel. An Integrated Optical-Digital Approach for Improving Image Restoration, Proc. 2003 AMOS Technical Conference, Maui, HI, 2003, on CD-ROM.

P. Pauca, S. Prasad, R. Plemmons, T. Torgersen and J. van der Gratch. Integrated Optical-Digital Approaches for Enhancing Image Restoration and Focus Invariance, Proc. Annual SPIE Meeting, San Diego, CA, 2003.

T. Torgersen and S. Prasad. A Fisher-Information Approach to Engineering Pupil Phase Diversity, AMOS Technical Conference, Maui, HI, 2003, on CD ROM.

P. Pauca, R. Plemmons, M. Giffin and K. Hamada. Unmixing Spectral Data using Independent Component Analysis and Non-Negative Matrix Factorization,. Proc. AMOS Technical Conference, Maui, HI, 2004.

P. Pauca, F. Shahnaz, M. Berry and R. Plemmons. Text Mining using Nonnegative Matrix Factorizations, Proc. SIAM Inter. Conf. on Data Mining, Orlando, FL, 2004.

J. Piper, P. Pauca, R. Plemmons and M. Giffin. Object Characterization from Spectral Data using Independent Component Analysis and Information Theory, Proc. AMOS Technical Conference, Maui, HI, 2004.

J. van der Gracht, P. Pauca, H. Setty, R. Narayanswamy, R. Plemmons, S. Prasad, and T. Torgersen. Iris Recognition with Enhanced Depth-of-Field Image Acquisition, Proc. SPIE Conference on Defense and Homeland Security, Vol. 5438, pp. 120-129, 2004.

D. Hope and S. Prasad. Information-theoretic metrics of image quality in phase-diverse speckle imaging, Proc. AMOS Technical Conference, Maui, HI, 2004.

S. Prasad, P. Pauca, R. Plemmons, T. Torgersen and J. van der Gracht. Pupil-Phase Optimization for Extended-Focus Aberration-Corrected Imaging Systems, Proc. SPIE, Advanced Signal Processing Al-gorithms, Architectures, and Implementations XIV, Vol. 5559, pp. 335-345, 2004.

R.J. Plemmons, M. Horvath, E. Leonhardt, P. Pauca, S. Prasad, S. Robinson, H. Setty, T.C. Torgersen, J. van der Gracht, E. Dowski, R. Narayanswamy, and P. Silveira. Computational Imaging Systems for Iris Recognition, Proc. SPIE, Advanced Signal Processing Algorithms, Architectures, and Implemen-tations XIV, Vol. 5559, pp. 346--357, August 2004.

P. Pauca, R. Plemmons, M. Giffin and K. Hamada. Unmixing Spectral Data using Independent Component Analysis and Non-Negative Matrix Factorization, Proc. AMOS Technical Conference, Maui HI, 2004, on CD.

J. Piper, P. Pauca, R. Plemmons and M. Giffin. Object Characterization from Spectral Data using Independent Component Analysis and

Information Theory, Proc. AMOS Technical Conference, Maui HI, 2004, on CD.

R. Narayanswamy, P. Silveira, H. Setty, P. Pauca and J. van der Gracht. Extended depth-of-field iris recognition system for a workstation environment, Proc. SPIE Vol. 5779, pp. 41-50, Biometric Technology for Human Identification II; Anil K. Jain, Nalini K. Ratha; Eds., 2005.

D. Fan and R. Plemmons, et al. Optimizing phase masks for iris recognition systems, Proc. Optical Society of America Conference on Computational Optical Sensing and Imaging, Charlotte NC, pp.34-36, 2005.

M. Horvath, P. Pauca, and J. van der Gracht. Optimized restoration
strategies for recognition of blurred iris images, 2005 Frontiers in Optics Conference Proceedings, 2005.

S. Prasad. Optical Preconditioning and Digital Image Restoration, Proc. SPIE, vol. 5896, 2005.

R. Barnard, P. Pauca, T. Torgersen, R. Plemmons, S. Prasad, J. van der Gracht, J. Nagy, J. Chung, G. Behrmann, S. Mathews, and M. Mirotznik. High-Resolution Iris Image Reconstruction from Low-Resolution Imagery, Proceedings of SPIE Conference (6313) on Advanced Signal Processing Algorithms, Architectures, and Implementations XVI, San Diego, CA, 2006.

Q. Zhang, H. Wang, R. Plemmons and P. Pauca. Spectral Unmixing using Nonnegative Tensor Factorization, Proc. ACMSE, pp. 531-533, 2007

P. Pauca, R. Plemmons, et al. PERIODIC: State-of-the-art Array Imaging Technology, Proc. ACMSE, pp. 544-546, 2007

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 26

(d) Manuscripts

A. Cichocki, R. Zdunek, S. Choi, R. Plemmons, and S. Amari. Novel Multi-layer Nonnegative Tensor Factorization with Sparsity Constraints. Preprint (10 pages). To appear in Proc. of the 8th International Conference on Adaptive and Natural Computing Algorithms, Warsaw, Poland, 2007.

A. Cichocki, R. Zdunek, S. Choi, R. Plemmons, and S. Amari. Nonnegative Tensor Factorization using Alpha and Beta Divergencies. Preprint (12 pages) 2006. To appear in Proc. of the 32nd International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Honolulu, 2007.

M. Ng and R. Plemmons. Blind Deconvolution and Structured Matrix Computations with Applications to Array Imaging. Preprint (46 pages), 2006. Invited Chapter written for the book "Blind Deconvolution: Theory and Applications", to be published by CRC Press, 2007.

S. Prasad. Fischer-information based analysis of low resolution image sequences, submitted to J. Optical Soc. Amer., 2007.

Number of Manuscripts: 4.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Daniel Fan, summer 2005	0.50
Ryan Barnard, 2006	0.25
Brian Gray, 2006	0.15
Harsha Setty, WFU Medical School, 2(	0.25
FTE Equivalent:	**1.15**
Total Number:	**4**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
None	
FTE Equivalent:	
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Robert Plemmons, each year	0.11	No
Paul Pauca, each year	0.22	No
Todd Torgersen, each year	0.11	No
FTE Equivalent:	**0.44**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Emily Leonhardt, 2005-2006	0.20
Michael Horvath, 2005	0.20
FTE Equivalent:	**0.40**
Total Number:	**2**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

Percent of students graduating with undergraduate degrees in science, mathematics, engineering, and technology fields: ......

Percent of graduating undergraduates who continue to pursue graduate and Ph.D. degrees: ......

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): ......

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: ......

Number of graduating undergraduates who intend to work for the Defense Department: ......

Number of graduating undergraduates who will receive scholarships or fellowships: ......

Names of Personnel receiving masters degrees

NAME	
Daniel Fan, 2005	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
None	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED	
Kyle Gallivan, consultant 2001	0.11	No
Xiaobai Sun, consultant 2001	0.11	No
Dave Munson, consultant 2001	0.11	No
Sudhakar Prasad, consultant 2002-20	0.11	No
Harsha Setty, consultant 2002-2007	0.22	No
Joe van der Gracht, , consultant 2002-	0.30	No
FTE Equivalent:	**0.96**	
Total Number:	**6**	

Sub Contractors (DD882)

1 a. CDM Optics, Inc

1 b. 4001 Discovery Drive
Suite 130
Boulder CO 80303

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): CDM Optics disigned a camera system for delivery to the NSA for the purpose of extending the ima

Sub Contract Award Date (f-1): 7/1/2003 12:00:00AM

Sub Contract Est Completion Date(f-2): 12/1/2003 12:00:00AM

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1 a. CDM Optics, Inc

1 b. 4001 Discovery Drive
Suite 130
Boulder CO 80303

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): CDM Optics disigned a camera system for delivery to the NSA for the purpose of extending the ima

Sub Contract Award Date (f-1): 7/1/2003 12:00:00AM

Sub Contract Est Completion Date(f-2): 12/1/2003 12:00:00AM

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1 a. The Catholic University of America

1 b. The Catholic University of America
620 Michigan Avenue, N.E.
Washington DC 20064

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): Reserchers in Electrical Engineering designed and fabricated two lenslet array imaging systems for

Sub Contract Award Date (f-1): 9/1/2006 12:00:00AM

Sub Contract Est Completion Date(f-2): 2/28/2007 12:00:00AM

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1 a. The Catholic University of America

1 b.

Washington DC 20064

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): Reserchers in Electrical Engineering designed and fabricated two lenslet array imaging systems for

Sub Contract Award Date (f-1): 9/1/2006 12:00:00AM

Sub Contract Est Completion Date(f-2): 2/28/2007 12:00:00AM

Inventions (DD882)

5 **Methods and systems for designing electromagnetic wave filters and electromagnetic wave filters designed using same**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) Y

Foreign Countries of application (5g-2):

5a: Paul Pauca, Robert Plemmons, Todd Torgersen

5f-1a: Wake Forest University

5f-c: Dept. of Computer Science, Manchester Hall

Winston-Salem NC 27109

FINAL REPORT

Innovative Computational Methods for Inverse Problems in Optical Imaging Novel Image Quality Control Systems (Add-Ons)

Grant: DAAD19-00-1-0540, PI - Robert J. Plemmons

Forward

In the past decade imaging systems have become ever more ubiquitous as electronic systems have substituted for humans to provide security and protection. High-resolution images are of course essential in many important applications in defense, science, engineering, law enforcement, and commercial areas. The need to extract meaningful information from degraded images is especially vital for personnel identification using biometrics technology such as iris identification. Imaging has traditionally been defined as a process of measuring object attributes (potentially time varying) as a function of spatial coordinates. The most familiar visible-light imaging technology is provided by the venerable camera, whose lens collects light generated or reflected by objects and maps it onto a light-sensitive medium (film or electronic sensors), thereby capturing a representation of the spatial distribution of the objects within the constraints of a particular 3D to 2D mapping. Recent advances in technologies for optical wavefront manipulation, optical detection and digital post-processing have opened new possibilities for imaging systems in the visible and IR regimes, suggesting the development of imagers which differ dramatically in form, fit and function from time-honored camera designs.

The objectives of this project were to conduct rigorous mathematical and computational research on inverse problems in optical imaging of direct interest to the Army and also the intelligence agencies. Research problems included enabling mathematics research in integrated optical systems design, personnel identification and verification using biometrics, and compact lenslet array imaging camera systems. A novel approach for improving image quality involved encoding of the phase by an optical mask, followed by digital filtering to decode the phase and restore the image. Our numerical optimization-based technique of combining optical/electronic hardware with digital processing is associated with our work on what we call Pupil-Phase Engineering (PPE).

This ARO project was primarily funded over the last three years by supplements from the Biometrics Division at the NSA, the Intelligence Technology Innovation Center at the CIA, and the Disruptive Technology Office (DTO), under the Director of National Intelligence.

Technology transfers included the transition of our extended depth-of-focus research to the ARL in Adelphi, MD, to the Army Night Vision Lab at Ft. Belvoir, VA, and to Biometrics research related intelligence work at the NSA, CIA and DTO. Industrial technology transfer took place with Iridian Technologies Company in Moorestown, NJ, CDM-Optics Company in Boulder, CO, and Sarnoff Corporation in Princeton, NJ.

A total of 20 research publications have appeared in peer-reviewed journals, and 26 as peer-reviewed conference papers were published, for a total of 56 published peer-reviewed papers. Also, 3 additional papers are in press, 1 is currently submitted and 4 are in preparation. A total of 55 invited conference presentations were made during the grant period.

Table of Contents

1. Statement of the Problems Studied

Listed next is a summary of some of the problems we have considered during the grant period. More specific details on the major results obtained on these and related topics are provided in Section 2.

1.1. Algorithms for Image Reconstruction

The objectives of our work in the area of image reconstruction were to conduct research on inverse problems arising in image post processing using blind deconvolution techniques and phase retrieval. High-resolution images are essential in many important applications in defense, science, engineering, law enforcement, and medicine. Fast and efficient iterative reconstruction methods have been essential for our development of (i) optimization-based pupil-phase engineering methods for design of optical imaging systems, for our work in (ii) making iris recognition systems user friendly, and for the (iii) design, optimization and fabrication of lenslet-based, compact, low-cost, multi-aperture imaging systems with a wide field of view, that can incorporate spectral, polarization, extended depth-of-focus, and other diverse modalities.

We have published several papers on effective image reconstruction algorithms and applications (see references [1 - 8, 10 - 11, 13 - 14, 17, 27, 29 - 32]) under support from this ARO grant.

1.2 Pupil-Phase Engineering (PPE)

Our work on PPE involved the rigorous mathematical research on design optimization problems arising in the areas of: (i) integrated imaging systems design and implementation for image quality control, (ii) image post processing using blind deconvolution techniques and phase retrieval, as well as (iii) accurate corrections to the phase aberration problems encountered in both optical and synthetic aperture radar systems. The need to extract meaningful information, not always visual, from degraded images is especially vital for such DOD applications as integrated optical imaging systems, surveillance photography, and modern synthetic aperture imaging systems. Sources of image degradation vary among application areas, but include atmospheric turbulence, turbidity in a fluid medium, defocus blur, motion blur, insufficient sampling, electronic noise, and other effects. We have made substantial progress in developing integrated optical imaging systems and algorithms to remove phase aberrations associated with defocus. In particular, progress has been made on a project on the important topic in optical-digital imaging for restoring extended field of focus blurred images. The depth of focus of an imaging system is the distance in the image space in which objects are considered to be in focus. This work has had Army applications to the Army Tank Command in developing new navigational imaging systems, as well as night vision IR imaging applications.

We have published several papers on pupil-phase engineering applications, as described in references [5, 8 - 9, 12, 16, 18 - 20, 23, 33]. See, especially the invited paper [20] for extensive details on our Pupil-Phase engineering work for this ARO project.

1.3 Biometric Iris Recognition

Our biometrics work was funded in part by supplements to the ARO grant from the Biometrics Division at the NSA, and the Intelligence Technology Innovation Center at the CIA.

The goals of the iris recognition project included providing novel and extensive research in **Pupil-Phase Engineering** (PPE) in order to help develop, in partial collaboration with our industrial contractor CDM Optics Company (CDM), a reliable, easy to use, low cost iris recognition system for personal verification, in part for computer access security at government facilities. The primary technical goal of the project was to make iris recognition easier to use by greatly expanding the iris capture volume of the imaging system. Our methods can increase the iris capture volume by several magnitudes compared to current iris recognition systems. Our additional work builds on a growing understanding of the optimization strategies as well as a more in-depth understanding of the requirements of the iris recognition algorithms. Phase-encoding optical images in the pupil plane and then digitally restoring them can greatly improve their quality by removing certain aberrations such as defocus. The design of overall optical masks is a non-trivial problem and involves the numerical solution of highly non-linear and ill-posed optimization problems with multiple design parameters. The Wake Forest Group (WFG) has used in our tests an algorithm developed by John Daugman at Cambridge University in England, and licensed to Iridian Technologies in Moorestown, NJ. For comparison purposes, CDM used an alternate algorithm in their tests. The Daugman approach we used was shown to be superior.

Algorithms and software systems developed as part of our iris recognition research project are described in references [21 -22, 24 - 26, 28, 34]. Prototype iris recognition camera systems, optimized by our PPE methods for various scenarios, are being delivered to the intelligence agencies in May 2007.

1.4 Array Imaging

During the last few months of the grant we received supplemental funds from the Disruptive Technology Office (DTO) to cover work over the period 9/1/2006 through 2/28/2007. The objective here is to design, optimize, and fabricate a compact, low cost, multi-aperture array imaging camera with diverse modalities for the intelligence agencies, with multiple applications of interest to the intelligence agencies, as well as to the DOD.

Research on the important topic of array imaging technology is still being funded by the DTO, although the ARO grant ended February 28, 2007. Demonstrations of a prototype system have been made to various representatives of the DOD, including the U.S. Special Operations Command (SOCOM), headquartered at Tampa, FL, and the Army Night Vision Laboratory, at Ft. Belvoir, VA.

Our initial work on this array imaging and integrated computational imaging technology is reported in references [35 - 37].

2. Summary of the Most Important Results

2.1 Image Reconstruction, Pupil-Phase Engineering, and Applications to Iris Recognition

For the application area of iris recognition, the Wake Forest Group (WFG) has designed Pupil-Phase engineered optical element surfaces, developed nonlinear optimization based iterative algorithms and modeling software, and performed experiments with our systems. The WFG has used this technology to gain significant knowledge of the iris recognition problem from an optics design perspective, and delivered both simulation software and a prototype imaging system.

Figure 1 illustrates some of our recent PPE design optics tests in extending the depth of focus for iris image data provided to us by Iridian Technologies, using in part software supplied by Iridian based upon an algorithm by Daugman, from Cambridge University in England. In our experiments we simulated insertion of a PPE phase mask into the camera imaging system to significantly extend the focal depth, and then we restored the intermediate blurred image. Authentication of the restored iris image proved successful.

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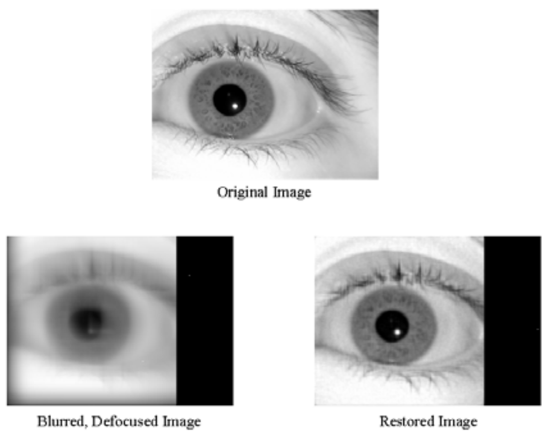

Figure 1. Design optimization tests by the WFG, based in part on the Daugman algorithm.

A critical requirement of a robust iris recognition system is a reliably high quality of the iris images it must routinely acquire both at the enrollment and authentication stages. To achieve this, the imaging system must possess a reasonably high depth-of-field and insensitivity to aberrations while allowing sufficient light throughput to record images accurately. Stopping down the aperture is not a viable option. While increasing the depth-of-field and reducing aberrations, stopping down the aperture reduces both the light flux and the native resolution of the images.

In recent years, the Wake Forest Group has applied information theoretic optimization approaches to improving the depth-of-field of a camera. Called Wavefront Coding by CDM, the original idea sought via a simple modification of the pupil phase to decrease the sensitivity of the MTF of the optical system to misfocus errors. Although the images produced in this way have a lower quality than without any pupil-phase modifications, the depth insensitivity of the images permits them to be deconvolved in a space-invariant fashion and thus improve the overall resolution of the images

without compromising the achieved depth insensitivity. Our more general approach, called **Pupil-Phase Engineering** (PPE), is a nonlinear optimization approach that seeks to determine the best pupil phase distribution that achieves a balance among various competing requirements of high SNR, sought depth-of-field, restorability, etc.

We may parameterize the pupil phase in a number of ways. The simplest, and perhaps least biased, phase profile $\varphi(x, y)$ is symmetric under the interchange of x and y and is odd under inversion in the (x, y) plane, its oddness leading to a PSF whose Taylor expansion in the misfocus parameter has only even-power terms. Ignoring the linear terms, we take the phase to have the following form:

$$\varphi(x, y) = a(x^3 + y^3) + b(x^2 y + x y^2) + c(x^5 + y^5) + d(x^4 y + x y^4) + e(x^3 y^2 + x^2 y^3) + \ldots$$

This polynomial expansion for the phase is truncated at a finite number of terms and the values of the coefficients of the retained terms are optimized by means of one of a number of possible depth-extension and image restorability criteria. We have employed three different criteria in our past work: (i) insensitivity of Strehl ratio (on-axis PSF) to defocus, (ii) Fisher-information-based insensitivity of the full PSF over the desired defocus range, and a minimax optimization formulation of the restorability of the phase-encoded image as measured by the integral of the MTF over allowed spatial frequencies. Technical details of these approaches were presented at the 49th Annual Meeting of the SPIE in Denver, August 2004. Note that the PPE approaches to extend the depth-of-focus also automatically achieve improved performance against any geometrical (Seidel) aberrations, except possibly coma, of the optical imaging system, making it possible to relax the relative desirability of on-axis versus off-axis imaging of the iris. In other words, there is not just increased focal depth but an increased focal volume that results from these approaches.

The additional work for this project in 2005-2006 was built on a growing understanding of the optimization strategies as well as a more in-depth understanding of the requirements of the iris recognition algorithms. In particular, we designed and simulated new effective optical masks especially tailored to extend the depth-of-field in iris recognition imaging system. The aspheric optical mask with best depth-of-field performance under simulation was *fabricated* and tested in a laboratory setting. In addition we further developed theory and approaches for reducing the impact of other aberrations in iris imaging systems. We also initiated a study to examine the problem of extending the field-of-view by use of PPE to mitigate field-dependent aberrations, and thus to reduce the requirements on the lateral position of the subject. In all of these studies an examination of the SNR effect on the quality of iris recognition systems was considered. We also investigated the potential advantages of using an array imaging (compound-eye) camera for capturing high resolution iris images. Finally, we broke new ground with the introduction of “bruslets”, a refinement of the wavelet paradigm, as a means for encoding iris images. This approach may have advantages over the use of the older Gabor wavelet approach as used in the Daugman algorithm.

The Wake Forest Group deliverables to the intelligence agencies who sponsored this project through supplements to the ARO grant included the following items:

- Reports in the form of research publications were provided on the results of the investigations.

- An upgraded iris recognition simulator system was provided by our group. The simulator was installed on a high-performance laptop computer with associated software, including Matlab, for delivery to the sponsors. It contains software to enable testing of a "virtual array imaging camera" for iris imaging applications.
- A pupil-phase engineering optimized optical element for extending the depth-of-focus, was fabricated, tested, and inserted in a scientific camera for delivery to the sponsors, as part of our work on this Army Research Office grant.

2.2. CDM Optics, Inc., Subcontractor Report

Given here is a report on some work by our subcontractor in developing a deliverables for the intelligence agencies through the ARO grant to Wake Forest University.

"Extended Depth of Field for Computer Security Iris Recognition"
CDM Optics' 2004-2005 report on the Iris recognition project, delivered to Prof. Robert Plemmons, Wake Forest University, March 2, 2005

CDM Contact Information

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Phone 303.449.5593 x 116

Introduction

Iris recognition is being embraced as a biometric for computer access and other security applications. The user is allowed access to the computer if his/her iris matches one of the pre-enrolled irises. The recognition system consists of a camera connected to the computer which captures an image of the iris at near infrared wavelengths. The ideal camera for such a human-use application would be one with a large field of view, large depth of field and efficient in capturing light. Availability of such a camera would make the verification process almost "transparent" and operate without the user making a conscious effort to cooperate.

CDM Optics' Wavefront Coded® imaging technology can expand the imaging volume without sacrificing the light-capturing capacity of the imaging system. In this project CDM Optics is tasked with developing Wavefront Coded optics to extend the depth of field of a computer recognition iris recognition system.

Technical achievements

In 2004 CDM Optics made considerable progress in this project, with the help of the **Wake Forest Group**, especially interaction with Harsha Setty, Paul Pauca and Joe van der Gracht. In particular, Harsha Setty compiled the Hamming distance tests reported here. **Phase I** of this work consisted of some preliminary studies. The notable achievements for **Phase II** and **Phase III** are as follows:
Phase II achievements:

- Characterized the iris recognition algorithm in terms of the spatial frequencies of importance to the iris recognition algorithm, the minimum required resolution, and illumination levels for good SNR at the detector.
- Specified the Wavefront Optics and signal processing to be designed

- Successfully fabricated a molded Wavefront Coded element
- Built a Wavefront Coded imaging system for the computer security application and demonstrated a depth of field from 18” to 28” with a nominal working distance of 24”
- Developed a relationship with Sarnoff Corporation and transferred the technology to them

Phase III achievements:

- Initiated the design for the Phase III of the project, where the person has to be identified at a distance of approximately 1.5 meters or beyond.
- Specified the Phase III Wavefront Coded optics
- Considered a wide range of designs given our past experience in this application. Five different designs were evaluated and one of the five designs has been chosen for fabrication.

Illustration of Phase II results

Figure 1 in this attached CDM Report shows a comparison of the performance of both the traditional and Wavefront Coded iris recognition systems. Iris images are acquired by each system at object distances of 20”, 24” and 28” when the each of the imaging systems are focused at an object distance of 24”. The Wavefront Coded imaging system is fitted with the custom designed Wavefront Coded optical element, and the acquired images have been filtered as part of the processing step. Notice that the Wavefront Coded images show fine detail such as eye-lashes and skin texture in all three distances, whereas the traditional images appear very blurred when out of focus. Iris images often present specular reflections due to the reflection of the illuminating light sources by the cornea. In the traditional images, the specular reflections are circular while in the Wavefront Coded images they posses a peculiar shape. This is a characteristic of Wavefront Coded systems, whose point-spread functions are often non-circular and take on a variety of shapes due to the asymmetry of the pupil function. Also note that the specular reflections have been partially removed from the Wavefront Coded images as part of the iris recognition processing. Figure 2 in this attached CDM Report illustrates the final result of our Phase II effort and it shows that Wavefront Coded optics extends the depth of field from 18” to 28”. The graph compares the iris identification Hamming distances (HD) as the user moves from a distance of 18” to 30” at 0.5” increments. The HD is a measurement of the fractional difference between bits in two given binary iris codes. A lower HD indicates a good match, whereas a HD higher than 0.3 indicates a mismatch. The HDs are plotted for an “authentic” or valid user. An “imposter” or a non-user would have HDs consistently around 0.45. Ten images are captured at each object position and the HDs are calculated for each of the ten images. Then, the average of the ten HDs are calculated and represented by a diamond-shape in Fig. 10. A threshold value of 0.2 provides us with accurate iris recognition from 23” to 25.5” for the traditional imaging system, whereas in the Wavefront Coded system we have accurate iris recognition from 20.5” to 28.5”, which is an increase in the depth of field by a factor of three. Traditionally, increasing the depth of field by a factor of three requires moving from an F-number of 3.5 to an F-number of 10.5. However, the light captured at F/10.5 drops to 11.1% of the light captured at F/3.5. Eye-safety illumination levels and motion blur limit ones capability to compensate for the loss in light power by increasing the illumination power or the exposure time by a factor of nine, thus maintaining the same SNR as that achieved at F/3.5. Should increasing the illumination or exposure time be possible, the application still would not attain the required depth of field using a traditional system, since diffraction effects present at F/10.5 would lead to loss in contrast and lower SNR at the higher spatial frequencies.

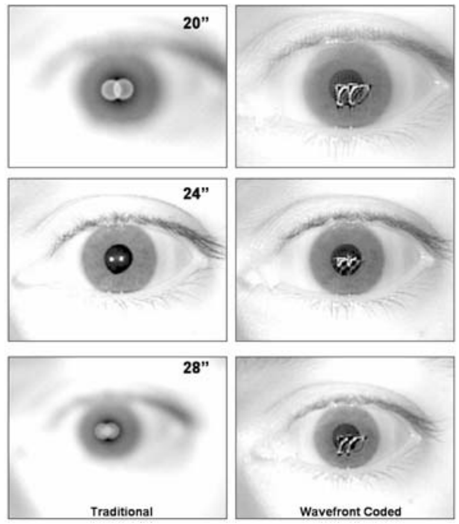
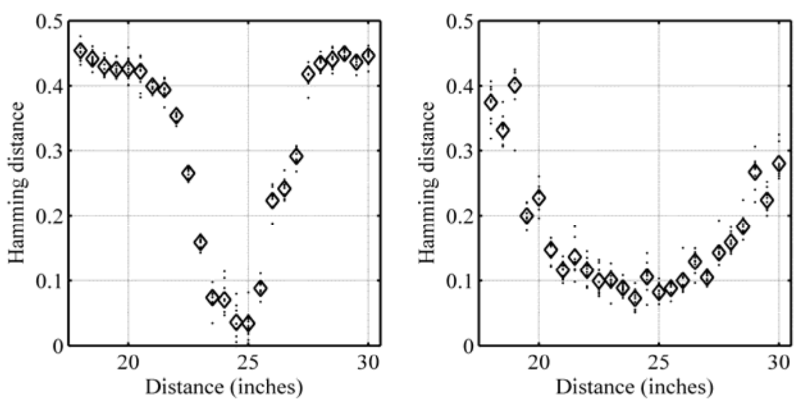


Figure 1: Comparison between images of eyes captured with a traditional imaging system (left) and a Wavefront Coded imaging system (right) at object distances of 20”, 24” and 28”. Both systems use a 50mm lens operating at F/3.5. The lens is focused at an object distance of 24” and not refocused as the object ismoved away from the best focus position.



(a) Traditional System **(b) Wavefront Coded System.**

Figure 2: Comparison between iris Hamming distances (HD) as the user moves from an object distance of 18" to 30" away from the imaging system. Ten images are captured at each position. The corresponding HDs are shown as dots and the averages of the ten HDs at each position are shown as diamonds. Setting a threshold of 0.2 provides a 2.5” depth of field for the traditional imaging system (a). The Wavefront Coded system (b) is able to maintain the HD below 0.2 for a distance of 8”.

Technology Transfers by CDM

- Set up collaboration with Sarnoff Corporation. Sarnoff has been provided with the Wavefront Coded optics and the required signal processing for the Computer Security application. Sarnoff Corporation’s preliminary investigation shows that they are able to extend the depth of field of their iris imaging system compared to a traditional imaging system.
- Set up a collaboration with Iridian Technologies. Iridian has licensed their Iris recognition software to CDM Optics.
- Eye Response Technologies are evaluating Wavefront Coded Optics to increase the depth of field for their eye tracking camera.

2.3 Wake Forest Group Iris Recognition Project Individual Activities

Project Leader: Robert J. Plemmons (Reynolds Professor of Computer Science and Mathematics, Wake Forest University)

The Project Leader has provided overall direction and research leadership for the iris recognition project, including the distribution of the funding and the delivery of specified deliverables to the sponsoring agency. He also collaborated extensively on the research activities under way throughout the project. His tasks address algorithmic, computational and implementation issues. These tasks enable the transition from theoretical development to prototype development and practical deployment of a reliable, robust, and cost effective iris recognition system. His activities included:

- Working closely with the full research team and subcontractor CDM Optics Company on iris recognition phase masks design optimization problems for pupil phase engineering methods for simultaneously extending depth of focus and maximizing information in recorded data.

- Interacting with the Research Sponsoring Agencies by coordinating meetings and briefings on the ongoing activities of the Iris Recognition project in 2004.

- Helping to design, test and mathematically evaluate numerical methods for solving related non-linear optimization problems using Pupil Phase Engineering and collaborate with the research team to develop real time algorithms for restoring the intermediate iris images.

- Working closely with co-investigators, consultants, industrial partner CDM Optics Company, Iridian Technologies, and Sarnoff Corporation in the development of new approaches for balancing fundamental trade-offs between restorability and extended depth of focus, as well as removal of related aberrations that could affect the performance of the target iris recognition imaging system.

Senior Computer Scientist: Todd C. Torgersen (Wake Forest University)
The Senior Computer Scientist has worked with the PPE project since its beginnings. His background is in Computer Science, with experience in the area of algorithm development, parallel computing, and object-oriented software design. His activities in 2004 included:

- Participation in the development of PPE methods including stable numerical formulations, fast computational methods, and implementation issues.

- Use of high performance computing equipment supplied to our project by the ARO for development of state-of-the-art global optimization techniques to design novel phase encoding filters over a variety of polynomial and functional bases.

- Collaboration with co-investigators and consultants in the development of new metrics for balancing fundamental trade-offs between restorability and extended depth of focus. He has derived fast methods for key calculations used by the Fisher information based metrics in close collaboration with grant co-investigators.

- His work to date has made significant use of a simulator he developed for modeling spatially-varying blur and the effect of a phase encoding element. He has performed extensive re-installation and re-configuration of an ARO supplied 32 processor Silicon Graphics Origin 2000 system, used for simulations and optimization computations, and ported codes to the Origin 2000 environment. He has obtained (using the Origin 2000) a globally optimal filter for extended depth of focus in the case of a symmetric polynomial basis of total degree five.

- He has worked closely with the WFU Office of Technology Management to make a provisional patent application covering our PPE methodology, and resulting novel designs. The patent application has been filed.

Junior Computer Scientist: V. Paul Pauca (Wake Forest University)

The Junior Computer Scientist has worked with the PPE project for the past three years. His background is in Computer Science, with expertise in many aspects of scientific computation including development of fast numerical algorithms, parallel computing, and software design and implementation. His activities in 2004 included:

- **Efforts in support of CDM Optics.** He, along with Harsha Setty, has collaborated with CDM Optics in the testing of HOS, a new wavefront encoded element especially designed by CDM Optics for computer authentication via iris recognition. Most of the testing work was carried out by Harsha Setty at Wake Forest using enver, an implementation by Iridian Technologies, Inc. of Daugman's iris recognition algorithm. This collaboration has resulted on a paper to be presented at the SPIE Defense & Security Symposium in April 2005.

- **Optical element design using PPE based optimization techniques.** We have explored the parameter space of optical elements represented by symmetric polynomials of degree 3 and 5, using our Fisher information and minimization-maximization based formulations. Defocus blur as well as spherical aberrations were considered. In addition, we continue our efforts to explore larger parameter spaces for example those that include polynomials of degree 7. Optical elements resulting from this investigation will be thoroughly evaluated in simulation in order to validate their performance before fabrication.

- **Frequency bandwidth studies.** We have conducted an experimental study that identifies the range of frequencies that are most important for iris recognition. The results obtained in this investigation have provided additional guidance to our optimization efforts and furthermore have enabled the development of better and more robust restoration algorithms. We are currently in the process of drafting a paper on this topic.

- **Continued optimization efforts to tune PPE for biometric iris imaging**. We have recently started the investigation of methods for utilizing enver as a part of the optical element design optimization process. This is a promising new research direction that may yield optical elements whose performance is especially tailored for iris recognition via Daugman's algorithm. The basic idea is to minimize the Hamming distance metric directly over the desired distance range. Figure 1 illustrates the motivation for this work. Optical elements that may

result from this investigation will be thoroughly evaluated in simulation and considered for potential fabrication. Daniel Fan, a graduate student in Computer Science and Michael Horvath, a senior undergraduate student, participated in this work.

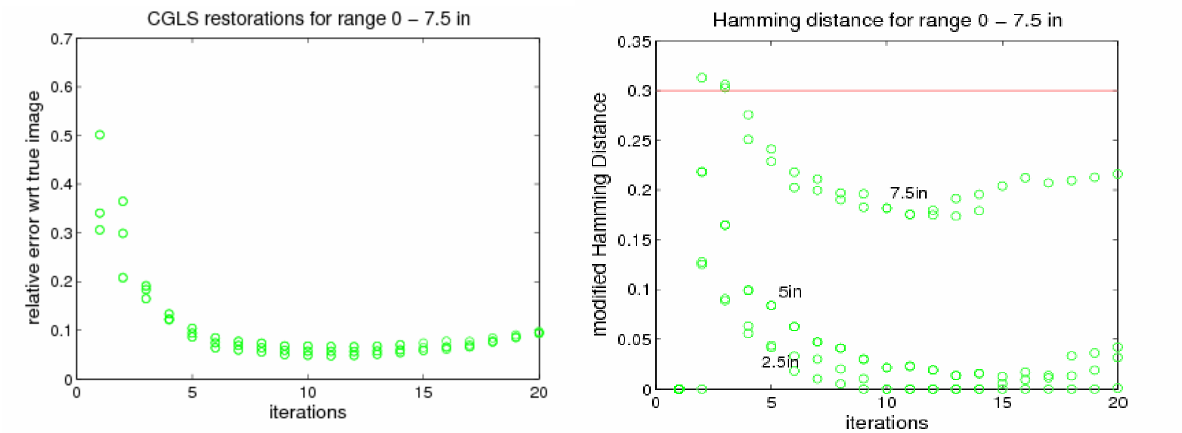


Figure 2. The plots show that restorations of PPE-encoded iris images captured at various distances from the camera are insensitive to defocus distance (left). However the restorations are *not* insensitive in terms of the Hamming distance, i.e. the metric used for iris recognition.

- **Further development of SIRIS.** We continue to work on enhancements to our Simulator of Iris Recognition Imaging Systems (SIRIS) software in view of future work for the intelligence agencies. The enhancements include:
  - A module for the evaluation of performance in terms of Hamming distance when an iris is placed at N different locations along the optical axis within a pre-specified distance range around the plane of focus. This module effectively simulates the imaging of an iris using a "camera on a motorized rail" system.
  - Improvements to the iris recognition interface so that the diameter of the iris can be passed as input to enver when the iris is located at non-standard distances from the camera.
  - Improved restoration algorithms that take advantage of frequency bandwidth during the restoration process. We have also implemented and evaluated robust direct restoration techniques.

Figure 3 shows a screen capture of the current version of SIRIS under Matlab version 7. We have also investigated the use of the Matlab compiler to generate an executable license-free version of SIRIS.

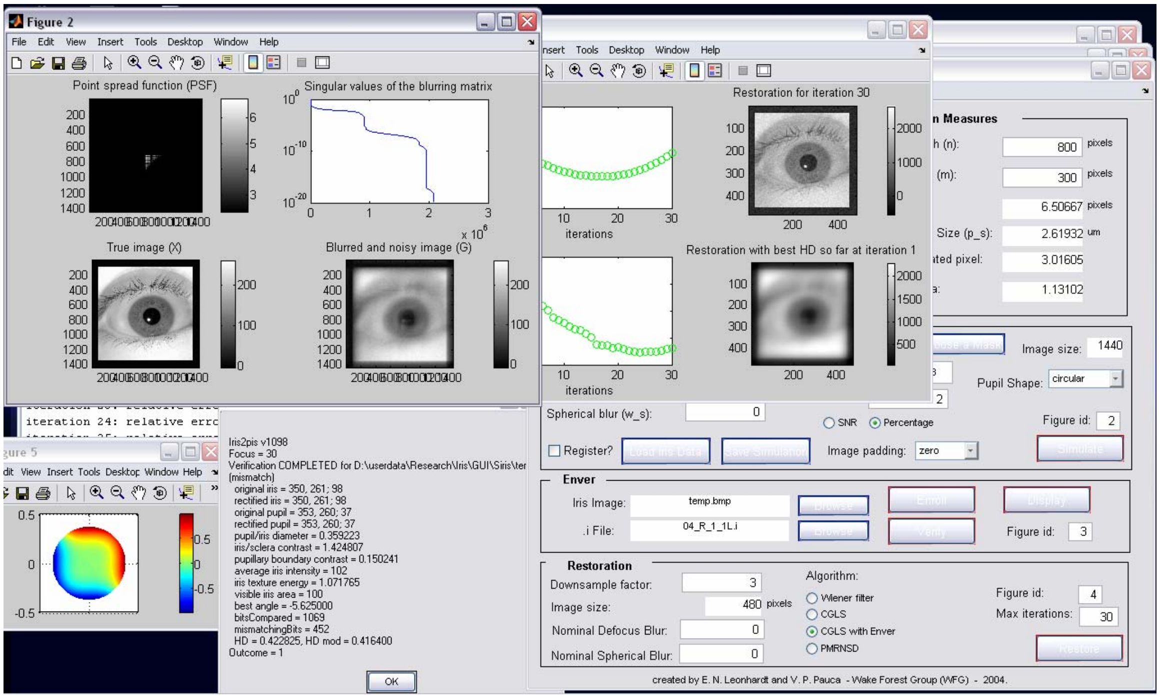


Figure 3. Screen capture of the SIRIS simulation system.

Senior Physics Consultant: Sudhakar Prasad (New Mexico)

The Senior Physics Consultant has long-standing research expertise in optical physics, particularly in the use of information theoretic methods in the analysis and optimization of the performance of a variety of imaging systems. His activities in 2004 included:

- The use of pupil-phase engineering (PPE) to design phase masks that compensate for random amounts of Seidel aberrations of the optical system. We have designed a 5^{th}-order phase mask by the use of a minimax optimization approach that lifts the integrated MTF of the imaging system above the noise floor and renders it approximately invariant over the desired range of aberration strengths. Such a pupil phase element has been demonstrated in computer simulation to lead to intermediate images that can be deblurred by means of a CGLS deconvolution algorithm leading to final images that exhibit excellent aberration invariance. This work, coupled with our continuing work on the use of PPE for focus extension, demonstrates the value of optical pre-conditioning, represented by the pupil-phase mask, in improving the ability of digital post-processing to enhance the final image quality against random variations of system aberrations and defocus. Because there is no need, with PPE, for corrective optics to quantify and remove aberrations for a given imaging system, our approach is likely to lead to inexpensive systems that are well optimized to image robustly under a variety of performance-limiting conditions.

- A new dedicated PPE design strategy is being analyzed for our iris-biometric system, which uses the Hamming Distance (HD) itself as the optimization metric. The basic idea is that any iris system must have an extremely low false positive authentication rate, as judged by the HD

between the authentication and enrollment images. To ensure this property against a range of possible focus variations, the following balance must be sought: For a given enrolled iris, any authentication images of it, regardless of the value of defocus (in a given, desired range), must produce iris codes that do not exceed 0.32 (the nominal HD threshold) in HD from the enrolled code; while two different enrolled irises must lead to two sets of authentication codes, over the same range of defocus, that do not come any closer than 0.32 HD for any pair of such codes drawn one from each set.This pair of requirements is being implemented in a minimax formulation to yield better pupil phase masks that discriminate more robustly against competing irises.

- Among other activities that have had an impact on iris research in CY04:

    1. Publication of information theoretic calculations for a phase-diverse speckleimaging system this demonstrates the usefulness of Fisher information (FI) as an excellent metric of performance for imaging systems.
    2. Application of Shannon information and relation to FI for iris systems – our phase mask design based on an FI based optimization metric seems to have only marginal performance, when assessed using a Shannon-information metric. This dichotomy of information measures and their complex inter-relationship, as indicated by this observation, will be investigated in detail in the forthcoming months. This will help us develop a better understanding of the fundamental limits of performance, as calculated by means of these two information metrics, for focus-extended, aberration-compensated iris imaging systems.

- He has helped to combine our iris biometric research with research enabled by a very recent DTO Challenge workshop funding to demonstrate an array imaging system that integrates the PPE design strategy developed under the present funding with sub-pixel-shift-based digital resolution enhancement approach. This array system will not only achieve the high promise of an integrated computational imaging approach but also has the potential to lead to a miniature imaging system with high field of view, high resolution, excellent aberration/focus independence, and an ultra-thin aspect ratio. Such miniaturized systems are likely to be very useful for iris-based and other biometric surveillance applications.

Senior Engineering Consultant: Joseph van der Gracht (Holospex Inc., Columbia, Maryland)

The Senior Engineering Consultant has extensive experience in the theory and practice of phase encoding and pupil phase engineered systems. He performed the first recorded laboratory verification of the cubic phase extended-depth system. He has also published theoretical predictions and laboratory experiments related to the information capacity of imaging systems. His activities in 2004 included:

- Modified information density software tools to accommodate higher order separable (HOS) designs supplied by CDM Optics.

- Used information density tools to compare and contrast the use of cubic surfaces, CDM HOS surface and WFU PPE designs. Results suggest only nominal differences in

performance between cubic and HOS elements. Results for PPE designs call for a new optimization over larger depth-of-field.

- Used both simulations and laboratory data to investigate the use of parameterized Wiener filters to improve iris matching scores. Results demonstrated that only lower frequency portions of the iris spectra are significant for iris matching. Determined optimum parameters.

- Built a laboratory test system with a precision scientific camera for capture of standard and wavefront coded iris recognition imagery. This laboratory test system is pictured next.

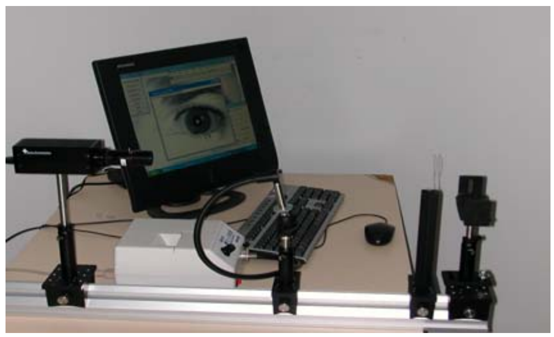


Figure 4. Laboratory system designed for iris recognition tests.

- Used information theory metrics to estimate the optimum parameter for a cubic phase element to extend the depth-of-field of an iris recognition system.

- Gathered a number of relevant data sets using the laboratory system with standard and cubic systems at a variety of different numerical aperture settings.

- Used the Iridian supplied implementation of the Daugman iris recognition algorithm to compare the depth-of-field of cubic phase and standard imaging systems. Best results showed approximately 10 inches of depth-of-field for a cubic system compared with 3 inches for a similarly configured standard system.

- Used the Iridian supplied recognition algorithm to explore the robustness of cubic phase systems. Identified a number of key issues including higher variance in iris signatures for wavefront coded systems and difficulties finding iris boundaries with wavefront coded images.

- Provided consultative assistance to CDM optics to construct their own version of an iris testbed and demonstrator.

- Constructed a demonstrator unit to allow sponsors to perform experiments using wavefront coded optics and the Iridian algorithm.

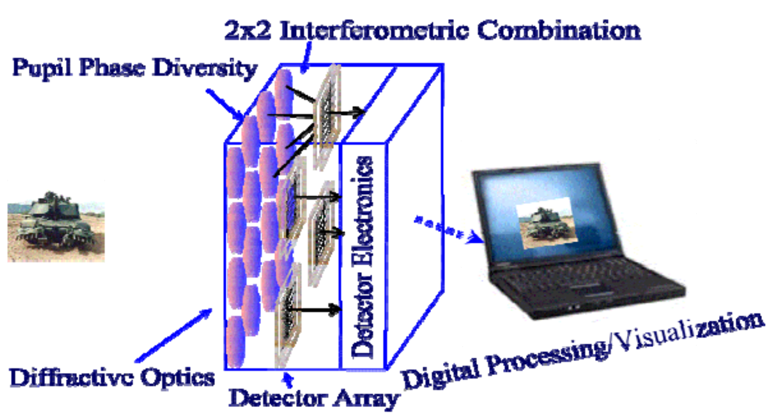
Junior Engineering Consultant: Harsha Setty (Wake Forest University School of Medicine, and 2LT, U.S. Army Reserve)

2LT Setty had experience in applying and testing iris recognition systems during his graduate education and participation in research activities at the Fitzpatrick Center for Photonics and Communications Systems at Duke University. In addition, he has been interacting with Dr. John Daugman at Cambridge University in England, who holds fundamental patents on iris recognition algorithms and associated software for enrollment and verification. His activities in 2004 included:

- Primarily assisted CDM Optics in evaluating the performance of phase mask coding systems (WFC) within the Daugman algorithm by conducting Matlab simulations.
- Provided assistance to CDM optics with laboratory experiments to compare WFC and standard imaging systems.
- Provided consultation to CDM optics to develop an Institutional Review Board (IRB) research protocol pending further experimentation needs.
- Conducted Matlab simulations with Paul Pauca for evaluating the performance of standard cubic phase elements within the Daugman iris recognition algorithm.

2.4 Development of the PERIODIC Lenslet Array Imaging System

This Distruptive Technology Office (DTO) sponsored project, A Practical Enhanced-Resolution Integrated Optical Imaging Camera (PERIODIC) System, aims to analyze, optimize, simulate, design, and fabricate a beta prototype, integrated, optical-digital, low-profile, low-cost, array-based imaging system. Considerable progress has been made in the theoretical, computational, and design fabrication aspects, leading to the development of very promising workable prototype systems. Although more complex, our PERIODIC camera has many features shown in the figure to the right. This effort, enabled with the help of the supplemental funds to the DTO, supported two graduate students and one undergraduate student, working with Professors Plemmons, Pauca, and Torgersen. Funds also purchased additional equipment and supplies by the design and fabrication group at Catholic University (CUA).



The objective here is to design, optimize a compact, low cost, array imaging camera with multiple diverse

modalities for the intelligence agencies, with multiple diverse applications. In particular, we seek to analyze, optimize, simulate, design and fabricate a beta prototype, integrated, optical-digital, low profile array-based imaging system for:

- Information collection, processing, and exploitation via array imaging.
- Acquisition of multi-channel image-information diversity.
- Post-processing of multi-channel information into one or more high-definition images.

Design and delivery of our thin profile, high dynamic range, high focal volume, computational imaging system meeting these objectives is the ultimate purpose of this work sponsored by the DTO through the ARO. The approaches to this work include research and development studies involving mathematical and engineering technology to optimize and fabricate an array camera system with low cost, and enhanced re-configurability. Some of these funds were used to support two graduate students at Wake Forest University, and some was used as a subcontract to The Catholic University of America, for fabrication of the imaging device.

One particular application of possible direct to the Army is the **Warfighter Payoff** – the potential of a low cost, compact, reconfigurable PERIODIC system to allow increase in battlefield image information without overwhelming Warfighter command centers with data.

3. Technology Transfers by the Wake Forest Group

This project provided a variety of new and important technologies in the form of robust and efficient algorithms as well as their implementations. Technology transfer includes the transition of our work to the DOD and research facilities, and to commercial companies with DOD contracts. In particular, the extended depth-of-focus and related imaging research technologies are being made available to intelligence agencies.

3.1 Technology Transfer to the ARL at Adelphi, MD.

Technology transfers here included the transition of our extended depth-of-focus research to Army research on imaging with Dr. Joseph Mait at the ARL in Adelphi, MD. Below is a statement from Dr. Mait at the ARL concerning the Army's use of our technology work:

"Cubic Phase Computational Imaging at Millimeter Wavelengths"
Joseph Mait, ARL, Adelphi MD. Justification for ARL's Interest in the Wake Forest University Analysis Tool Developed under ARO Grant DAAD190010540.

One application in which millimeter wave technology has a clear advantage over others is detecting weapons hidden under clothing. Within the frequency ranges of interest, cloth is effectively transparent to radiation. Thus, border and security personnel can use millimeter wave technology as an adjunct to metal detectors at checkpoints to search for individuals who pose a potential risk to others. In such scenarios, the range over which a millimeter wave imager needs to be used is sufficiently short that atmospheric attenuation is not a problem. At an entry point to a military compound, for example, one would like to funnel visitors through a checkpoint in such a way that a millimeter wave imager has an extended look at a person as they proceed to a point of egress. However, existing millimeter wave imagers, which operate at 94 GHz and below, suffer

from a short depth of field. To increase the depth of field one can develop new imagers that operate at higher frequencies (the focus of several DARPA programs) or one can use computational imaging techniques. In 1995, Cathey and Dowski were the first to demonstrate an extended depth of field at optical wavelengths using a cubic phase element in combination with post-detection processing. Since operation of the element is not unique to optical wavelengths, one can apply it directly to millimeter wave imaging. The difficulty is determining how best to implement the element and assessing the noise properties of the final processed image. Although techniques to encode the cubic phase are relatively straightforward to implement, the efficacy of computational imaging with a cubic phase at these frequencies needs to be demonstrated. The most critical issue to investigate is the effect of noise on the final image. The transfer function of the cubic phase element has a large on-axis term in comparison to the high frequency terms. For systems affected by signal dependent noise at detection, this can be deleterious. If the incident field consists of a low power signal in the presence of a large bias, noise is generated primarily by the bias and reduces the signal to noise ratio. The effect of this can be mitigated somewhat by controlling the total phase change across the cubic element. The greater the phase change, the greater the difference between the transmission of high and low frequencies. However, the greater the phase change the greater the increase in depth of field. Thus, the degree to which depth of field can be increased is limited by the system noise. We will investigate this trade-off between noise and depth of field. Another tradeoff we will investigate is that between the size of the optical point spread function and the field of view. To realize some benefit from the cubic phase element, its response must be large relative to an image pixel. In fact, the response should be at least 20 by 20 image pixels in size. However, a large response implies a small aperture, which limits the field of view. The ARL will investigate this trade-off between field of view and depth of field. Wake Forest University's analysis tool for cubic phase computational imaging will facilitate these investigations and allow ARL to proceed more quickly than otherwise if analysis software were to be designed from scratch.

2. Technology Transfers to the National Security Agency, and the ITIC.
The purpose of of these transfers were to enhance personnel verification and identification. Our contact person at the NSA for this technology transfer was Dr. Michael King, who later moved to ITIC at the CIA. The NSA and ITIC sponsors have provided this research grant project with supplemental funds in order for us to expand our work to include biometrics applications essential to their mission. (Some of this work with the NSA and ITIC is reported separately to them). We delivered a laboratory test system which included a precision scientific camera for capture of standard and pupil phase coded iris recognition imagery.

3. Technology transfer to the Disruptive Technology Office (DTO)
Our purpose is the designing, fabricating and testing low-profile, portable, efficient, and cost effective array imaging mult-aperture multi-diversity camera system. Our contact persons at the DTO for this technology transfer are Dr. Larry Skelly and Dr. Timothy Persons. The DTO sponsor provided this research grant project with supplemental funds in 2006 in order for us to expand our work to include research applications essential to their mission. We have fully demonstrated a prototype array imaging system to the DTO as well as DOD representatives in Washington, DC. Work on this project is continuing on a separate DTO grant.

4. Commercial technology transfers

These transfers were to Iridian Technologies in Moorestown, NJ, and Sarnoff Corp. in Princeton, NJ, for the purpose of improving their iris imaging camera systems used in personnel identification and verification. Biometrics systems such as iris recognition are critical to safeguarding information vital to national security. The U.S. Army has a direct interest in furthering research in biometrics and is working closely with other interested government agencies. Researchers on this ARO grant have worked closely with researchers from industry to study the effectiveness of extended depth-of-field for iris recognition. A successful outcome would enable iris verification without the need for the subject to maintain a critical distance from the camera. Researchers have already begun a laboratory experimental program to validate the process. In addition, new Fisher information-based theoretical work is leading to significant enhancement of the extended depth process. The research has also produced some important user-friendly simulation tools that have been delivered to the intelligence agencies, CDM Optics, Iridian Technologies and to Sarnoff Corporation.

Why this technology transfer is important: Iris recognition is arguably the most secure method of biometric identification. The chances of false acceptance are negligible. Unfortunately, the limited depth-of-field in current implementations require the subject to maintain the eye at a critical distance from the camera. For fully cooperative subjects this creates an annoyance that makes the enrollment process unattractive and prevents wide acceptance of this technology. Auto focusing systems are expensive and produce unwanted noise. Our ARO research efforts to apply extended depth-of-field imaging to iris recognition can mitigate these problems and provide an inexpensive and easy-to-use security system to protect important national assets.

4. ARO Grant Summary Statement

We feel that we have achieved the objectives of this project, which were to conduct rigorous mathematical and computational research on inverse problems in optical imaging of direct interest to the Army and also the intelligence agencies. Research problems included enabling mathematics research in integrated optical systems design, array imaging, and related imaging technologies. A novel approach for improving image quality involved encoding of the phase by an optical mask, enabled by our Pupil-Phase Engineering technology, followed by iterative methods for digital filtering to decode the phase and restore the image.

This ARO project was primarily funded over the last three years by supplements from the Biometrics Division at the NSA, the Intelligence Technology Innovation Center (ITIC) at the CIA, and the Disruptive Technology Office (DTO). Work on array imaging technology for the DTO is continuing.

5. References

1. W. Cochran, R. Plemmons and T. Torgersen. Exploiting Toeplitz Structure in Image Restoration, Contemporary Mathematics, Vol. 280, pp. 177-198, 2001.

2. J. van der Gracht, J. Nagy, P. Pauca and R. Plemmons. Iterative Restoration of Wavefront Coded Imagery for Focus Invariance. OSA Trends in Optics and Photonics (TOPS), Integrated Computational Imaging Systems, OSA Technical Digest, Washington, D.C., 2001.

3. P. Hemler, T. Persons and R. Plemmons. 3D Iterative Restoration of Tomosynthetic Images. OSA Trends in Optics and Photonics (TOPS), Integrated Computational Imaging Systems, OSA Technical Digest, Washington, D.C., 2001.

4. S. Prasad. Statistical Information Based Performance Criteria for Lucy Richardson Image Deblurring, J. Opt. Soc. Amer. A, vol. 19, pp. 1286-1296, 2002.

5. P. Pauca, A. Rodriguez, X. Sun, and K. Trivedi. A Methodology Towards Automatic Implementation of N-body Algorithms. Applied Numerical Mathematics, vol. 40, pp. 3-21, 2002.

6. M. Chu and R. Plemmons. Real-Valued Low Rank Circulant Approximation. Soc. for Industrial and Appl. Math J. on Matrix Analysis and Applic., vol. 24, pp. 645-659, 2002.

7. T. Torgersen and D. Tyler. Practical Considerations for Restoring Images from Phase-Diverse Speckle Data, Astonomical Soc. Pacific, vol. 114, pp. 671-685, 2002.

8. M. Chu, R. Funderlic and R. J. Plemmons. Structured Low Rank Approximation, Lin. Alg. and Applications, Vol. 366, pp. 157-172, 2003.

9. S. Prasad, T. Torgersen, P. Pauca, R. Plemmons, and J. van der Gracht. Engineering the pupil phase to improve image quality, in Proc. of the SPIE Vol. 5108 Visual Information Processing XII, edited by Z. Rahman, R. Schowengerdt, and S. Reichenbach, Wellingham, WA, pp. 1-12, 2003.

10. P. Pauca, S. Prasad, R. Plemmons, T. Torgersen J. van der Gracht, and C. Vogel. An Integrated Optical-Digital Approach for Improving Image Restoration, Proc. 2003 AMOS Technical Conference, Maui, HI, 2003, on CD-ROM.

11. P. Pauca, S. Prasad, R. Plemmons, T. Torgersen and J. van der Gracht. Integrated Optical-Digital Approaches for Enhancing Image Restoration and Focus Invariance, Proc. Annual SPIE Meeting, San Diego, CA, 2003.

12. T. Torgersen and S. Prasad. A Fisher-Information Approach to Engineering Pupil Phase Diversity, AMOS Technical Conference, Maui, HI, 2003, on CD ROM.

13. J.Mait, R. Athale, and J. van der Gracht. Evolutionary Paths in Imaging and Recent Trends, Optics Express, vol. 11, pp. 2093-2101, 2003.

14. S. Prasad, T. Torgersen, V. P. Pauca, R. J. Plemmons, and J. van der Gratch. Restoring Images with Space Variant Blur via Pupil Phase Engineering, Optics in Information Systems, Special Issue on Computer Imaging, vol. 4, no. 2, pp. 4-5, 2003.

15. J. Yuan, G. Golub, R. Plemmons, and W. Cecilio. Semi-Conjugate Direction Methods for Real Positive Definite Systems, BIT Numerical Mathematics, Vol. 44, pp. 189-207, 2004.

16. S. Prasad. Fisher Information Based Analysis of a Phase Diversity Speckle Imaging System, J. Opt. Soc. Am. A, vol. 21, pp. 2073-2088, 2004.

17. M. Catral, Lixing Han, Michael Neumann and Robert Plemmons. On Reduced Rank Nonnegative Matrix Factorization for Summarizing Video Sequences, Linear Algebra and Applications, Vol. 393, pp. 107-126, 2004.

18. S. Prasad and N. Menicucci. Fisher Information with respect to Cumulants, IEEE Trans. Information Theory, Vol. 50, pp. 638-647, 2004.

19. S. Prasad. Information optimized phase diversity speckle imaging, Optics Letters, Vol. 29, pp. 563-572, 2004.

20. S. Prasad, T. Torgersen, P. Pauca, R. Plemmons and J. van der Gracht. High-Resolution Imaging Using Integrated Optical Systems, International Journal on Imaging Systems and Technology, Vol. 14, No. 2, pp. 67-74, 2004. (invited paper)

21. R. Plemmons, M. Horvath, E. Leonhardt, P. Pauca, S. Prasad, S. Robinson, H. Setty, T. Torgersen, J. van der Gracht, E. Dowski, R. Narayanswamy, and P. Silveira. Computational Imaging Systems for Iris Recognition, Proc. SPIE 49th Annual Meeting, Vol. 5559, pp. 346-357, 2004.

22. J. van der Gracht, P. Pauca, H. Setty, R. Narayanswamy, R. Plemmons, S. Prasad, and T. Torgersen. Iris Recognition with Enhanced Depth-of-Field Image Acquisition, Proc. SPIE Conference on Defense and Homeland Security, Vol. 5438, pp. 120-129, 2004.

23. S. Prasad, P. Pauca, R. Plemmons, T. Torgersen and J. van der Gracht. Pupil-Phase Optimization for Extended-Focus Aberration-Corrected Imaging Systems, Proc. SPIE, Advanced Signal Processing Al-gorithms, Architectures, and Implementations XIV, Vol. 5559, pp. 335--345, 2004.

24. R. Plemmons, M. Horvath, E. Leonhardt, P. Pauca, S. Prasad, S. Robinson, H. Setty, T. Torgersen, J. van der Gracht, E. Dowski, R. Narayanswamy, and P. Silveira. Computational Imaging Systems for Iris Recognition, Proc. SPIE, Advanced Signal Processing Algorithms, Architectures, and Implemen-tations XIV, Vol. 5559, pp. 346--357, August 2004.

25. D. Fan and R. Plemmons, et al. Optimizing phase masks for iris recognition systems, Proc. Optical Society of America Conference on Computational Optical Sensing and Imaging, Charlotte NC, pp.34-36, 2005.

26. M. Horvath, P. Pauca, and J. van der Gracht. Optimized restoration strategies for recognition of blurred iris images, Annual OSA Frontiers in Optics Conference Proceedings, 2005.

27. S. Prasad. Optical Preconditioning and Digital Image Restoration, Proc. SPIE, vol. 5896, 2005.

28. M. Chu and R. Plemmons. Nonnegative Matrix Factorization and Applications, Bulletin of the International Linear Algebra Society, pp. 2-7, 2005. (invited paper)

29. S. Shahnaz, M. Berry, P. Pauca, and R. Plemmons. Document Clustering using Nonnegative Matrix Factorization, Information Processing and Management, Vol. 42, pp. 373-386, 2006.

30. J. Bardsley, S. Jefferies, J. Nagy, and R. Plemmons. A Computational Method for the Restoration of Images with an Unknown, Spatially-Varying Blur, Optics Express, Vol. 14, no. 5, pp. 1767-1782, 2006.

31. Z. Mu, R. Plemmons, and P. Santago. Iterative Ultrasonic Signal and Image Deconvolution for Estimation of the Complex Medium Response, International Journal of Imaging Systems and Technology, Vol. 15, no. 6, pp. 266-266, 2006.

32. P. Pauca, J. Piper, and R. Plemmons. Nonnegative matrix factorization for spectral data analysis, Linear Algebra and Applications, Vol. 416, pp. 29-47, 2006.

33. R. Plemmons. Inverse Problems in Imaging, in Computer Mathematics and Applications: Advances and Developments, Edited by E. Lipitakis, LEA Press, Athens, Greece, pp. 195-204, 2006.

34. R. Barnard, P. Pauca, T. Torgersen, R. Plemmons, S. Prasad, J. van der Gracht, J. Nagy, J. Chung, G. Behrmann, S. Mathews, and M. Mirotznik. High-Resolution Iris Image Reconstruction from Low-Resolution Imagery, Proceedings of SPIE Conference (6313) on Advanced Signal Processing Algorithms, Architectures, and Implementations XVI, San Diego, CA, 2006.

35. P. Pauca, R. Plemmons, et al. PERIODIC: State-of-the-art Array Imaging Technology, Proc. ACMSE, pp. 544-546, 2007.

36. M. Ng and R. Plemmons. Blind Deconvolution and Structured Matrix Computations with Applications to Array Imaging. Preprint (46 pages), 2006. Invited Chapter written for the book "Blind Deconvolution: Theory and Applications", to be published by CRC Press, 2007.

37. S. Prasad. Fischer-information based analysis of low resolution image sequences, Preprint Submitted to J. Optical Soc. Amer., 2007.